ANALYSIS OF SINTERED WC-TIC-6CO BY USING POWDER METALLURGY PROCESS

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ABSTRACT

Metal injection molding (MIM) is a process that combines the methods of plastic injection molding and powder metallurgy technology. In this study, the material used was tungsten carbide with 6wt% cobalt (WC-6Co) and titanium carbide (TiC) as grain growth inhibitor while low density polyethylene (LDPE) and palm stearin (PS) were used as a binder system. The sample was prepared by milling process consisting of WC-6Co at different wt. % of TiC (0.5, 0.75 and 1.0) before being mixed with binder system. The critical powder volume concentration (CPVC) obtained based on oil absorption technique is 47%. The rheological behavior was evaluated using capillary rheometer and it was conclude that all feedstock exhibit pseudoplastic behavior which is suitable to be injected where the sample with 0.75 wt. % TiC with 150ºC had the best rheological properties with activation energy of 37.68 kJ/mol, flow behavior index of 0.48 and moldability index of 1386.13. The taguchi parameter design was carried out to optimize the quality and density of the green body. The result shows the best combination parameter for minimizing warpage, shrinkage, and density value were obtained with a result of 0.0124 mm of warpage, shrinkage value improved by 33.34%, while for density, it can be inferred as improving about 1.63% which increased from 5.3968 g/cm^3 to 5.48486 g/cm^3. For the compaction method, WC-6Co were mixed with TiC by using ball mill mixer at 100 rpm for an hour. The characterization of the sintered samples was performed by X-ray Diffraction (XRD), Energy Dispersive Analysis (EDS), Hardness Test and Grain size analysis. The physical properties of WC-TiC-6Co was performed by using density test. At holding time 30 min, WC-0.75 wt. %TiC-6Co shows the highest density and hardness with the value of 10.2185 g/cm^3 and 102.3966 HV respectively. In addition, at this composition, the grain size produced is the smallest compared to the other samples. The addition of 1.0 wt. % of TiC was not favourable as it increase the grain size while decrease the hardness value of the sintered product.

ABSTRAK

Pengacuan suntikan logam (MIM) adalah proses yang menggabungkan kaedah teknologi pengacuan suntikan plastik dan metalurgi serbuk. Dalam kajian ini, bahan yang digunakan ialah WC-6Co dan karbida titanium (TiC) sebagai pemhambat pertumbuhan butiran (GGI), manakala polietilena ketumpatan rendah (LDPE) dan stearin sawit (PS) digunakan sebagai sistem pengikat. Sampel disediakan dengan proses penggilingan diantara WC-6Co dan TiC pada peratusan berbeza (0.5, 0.75 dan 1.0) sebelum dicampurkan dengan bahan pengikat. Pemadatan pepejal optimum (CPVC) diukur menggunakan tenik penyerapan minyak (oil absorption) memperoleh 47%. Ciri-ciri reologi aliran disiasat menggunakan reometer kapilari dan sampel yang mempunyai 0.75wt % serbuk TiC menggunakan 150ºC suhu adalah sifat rheologi yang terbaik dengan tenaga pengaktifan sebanyak 37.68kJ/mol, eksponen aliran sebanyak 0.48 dan indeks kebolehsuntikan sebanyak 1386.13. Proses pengoptimuman dijalankan bagi memaksimumkan produk kualiti dan juga ketumpatan jasad hijau, Tetapan parameter kombinasi terbaik digunakan untuk memperoleh nilai optimum untuk pelendingan dan pengecutan WC-6Co dengan 0.0124 mm nilai pelendingan manakala nilai pengecutan menurun sebanyak 33.34%. Nilai kepadatan juga bertambah sebanyak 1.63% iaitu dari 5.3968 g/cm^3 kepada 5.48486 g/cm^3. Untuk kaedah pemadatan, WC-6Co bercampur dengan TiC menggunakan pengadun berkelajuan 100 rpm selama satu jam. Pencirian sampel sinteran dilakukan oleh XRD, EDS, Ujian Kekerasan dan ujian saiz zarah manakala sifat fizikal menggunakan ujian ketumpatan. Pada masa persinteran 30 min, WC-0.75 wt. %TiC-6Co menunjukkan nilai kekerasan dan ketumpatan yang tinggi pada 10.2185 g/cm^3 dan 102.3966 HV. Tambahan pula, pada komposisi ini, saiz zarah yang terhasil adalah kecil berbanding sampel yang lain. Tambahan 1.0 wt. % TiC tidak diperlukan kerana menghasilkan saiz zarah yang besar dan menurunkan nilai kekerasan sampel jasad persinteran.

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LIST OF SYMBOLS AND ABBREVIATIONS

MIM	-	Metal Injection Molding
PIM	-	Powder Injection Molding
WC-Co	-	Cemented Carbide
TiC	-	Titanium Carbide
LDPE	-	Low Density polyethylene
PS	-	Palm Stearin
FESEM	-	Field Emission Scanning Electron Microscope
ANOVA	-	Analysis of Variance
DOE	-	Design of Experiment
%	-	Percentage
^{o}C	-	Celsius
wt. %	-	weight percent
s	-	Distance
p	-	Pressure
n	-	Speed
Z	-	Warpage
S	-	Shrinkage
T_{mould}	-	Mold Temperature in ^{o}F
$T_{ambient}$	-	Ambient Temperature in ^{o}F
UTHM	-	University Tun Hussein Onn Malaysia

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Injection molding is a process of shaping a plastic in a large quantity. Every year, over 6000 new molding machines were purchased to provide more than 10000 factories in the USA. Recently, only a polymer that melts over the heat can apply injection molding process. However, metals and ceramics have an excellent property and possible to exhibit electrical, magnetic, and thermal properties with polymers (German & Bose, 1997).

A new technology known as powder injection molding (PIM) is applicable for shaping metals and ceramics. PIM is a manufacturing process that combines the versatility and shape-making capability of plastic injection molding with the material flexibility of powder metallurgy (Asmawi et al., 2014) also known as metal injection molding (MIM) in metal field. The MIM process is intended to fabricate small and complex parts in large quantity which typically consists of four stages, mixing, injection molding, debinding and sintering (Arifin et al., 2015).

According to Heaney (2012), the first demonstration of PIM is unexpectedly the same as plastic injection molding. In the 1930s, the PIM was applied to produce a ceramic spark plug bodies in the USA and Germany followed by forming tableware in the early 1960s. About 80% of the production capacity of PIM recognized as MIM was devoted to metal in the 1970s. Ron Rivers (Rivers) patented the first MIM using a cellulose-water-glycerin wax-based binders.

Nowadays, there is an increasing tendency to produce components comprising of various materials through the MIM process. Cemented carbide (WC-Co) is widely used in industry for machining tools, cutting, mining and drilling tools as well as for wear-resistant equipment which require superior mechanical properties (Balbino et al., 2017). Their wide application stems from their combination of desirable properties, including large hardness, wear-resistance, and fracture toughness value (Al-Aqeeli, 2015).

In recent years, research and commercial interest are more into nano-cemented carbides with the carbide grain size of 100-500nm due to their extremely high hardness and wear resistance (Chen et al., 2016). Nano powder was introduced in PIM process due to the various studies of micro fabrication investigated for some reasons, and the particle size should be at least 10 times smaller compared to the minimum feature size. There are several benefits in powder processing when using nano powder. Better surface roughness and wear resistance as well as isotropic behavior were shown in the samples fabricated using nano powder. Lower temperature is needed during sintering process of nano powder compared to micro powder. However, large specific surface area of nano powder leads to high particles agglomeration and interparticle friction resulting in lower solid loading and high feedstock viscosity (Oh et al., 2017). Nowadays, in hard metal industry, the use of nano-crystalline WC powders for producing WC-Co materials with finer microstructure represents one of the most active fields of research (Chang & Chang, 2014).

1.2 Problem Statement

For the last several decades, the hardmetal research has been focusing on manufacturing submicron and nano-structured composites, whilst achieving a homogeneous and fully dense microstructure. Tungsten carbide-cobalt (WC-Co) cemented carbides are composite materials consisting of a high volume fraction of the hard hexagonal WC phase embedded in a soft and tough Co binder phase, which have wide application in wear resistance equipment, oil and gas drilling, mining and cutting tools due to their superior mechanical properties. It is well known that the mechanical properties of the WC-Co cemented carbides have been enhanced by WC grain size refinement to the submicrometer or nanometer scale (Chen et al., 2017). Thus, the control of the growth of WC is a key technique of ultrafine cemented carbide fabrication. So far, the most successful way to control the grain growth of WC is to add a small amount of other metal carbides into the original powder mixtures (Lauter et al., 2016). The addition of TiC in hardmetals could enhance the hardness and wear resistance of WC–Co cemented carbides. WC-TiC-Co alloy are generally better than WC-Co cemented carbide due to the hardness and wear-resistance of titanium carbide is higher than that of tungsten carbide (Lin et al., 2014). WC-TiC-Co cemented carbide can solve the problems of working softening, short life span and poor red hardness in practical applications (Chen et al., 2018).

In metal injection molding (MIM) technology, feedstock characterization is important because the properties of the feedstock affected the rest of the steps (molding, debinding and sintering) in MIM process. In order to reduce defects in the molded parts, the feedstock specifications should be consistent during injection molding. Each of the step during MIM process is affected by the thermal properties of the feedstock. During injection process, the binder system plays important role by providing the fluidity for the feedstock to easily fill the mold cavity, hence maintaining the shape of the molded part, and keeping the powder particles together. The binder behavior during molding, particularly its flow properties, is the most important condition to certify that no defect occurs in the product (Fayyaz et al., 2015). The defects can be controlled in subsequent processing steps by verifying the characteristics of the feedstock (Amin et al., 2013).

The molding stage is a crucial step for the fabrication of sound parts without cracks and distortions in MIM process. Defects during molding such as cracking and warpage occurred with non-homogenous flow and powder-binder separation lead to ultimately poor physical and mechanical properties of the final MIM component. Specific rheological behavior of a feedstock is required for successful manufacturing process. It has been extensively demonstrated that the knowledge of the rheology of feedstocks at different conditions is a key issue to allow proper optimization of process settings, to obtain good quality parts and thus optimize production costs (Hidalgo et al., 2017). Although considerable time and effort has been spent to resolve the problems encountered during the fabrication of MIM parts, defects still frequently occur in daily practices (Heaney, 2012). However, the product produced may have some defects that come from improper parameter setting in injection molding machine. Thus, to produce good quality product, suitable parameter selection is important.

1.3 Objectives

The objectives of this study are:

1) To characterize the properties of feedstock consist of WC-6Co, TiC, palm stearin (PS) and low density polyethylene (LDPE) for injection molding process.
2) To optimize the injection molding parameters on minimizing warpage and shrinkage and maximizing density of the green part.
3) To characterize the properties of sintered WC-TiC-6Co by using different sintering holding time and GGI weight percentage.

1.4 Scopes of Study

The scopes of study are:

1) The metal powder used in this study was WC-6Co with an average size of 40-50μm. Different amount of TiC wt. % (0.50, 0.75 and 1.0) was added to the starting powder by milling process using ball mill mixer.
2) The characterization of raw materials such as DSC, TGA, FESEM, EDS and CPVC were done before proceeding with the MIM process.

3) The binders used in this study were 60% of palm stearin (PS) and 40% of low density polyethylene (LDPE) and mixed with powder material to form a feedstock by using Brabender Plastograph mixer.
4) The feedstocks undergo rheology test to determine the effect of TiC towards the rheological behavior such as flow behavior index, *n*, activation energy, E and moldability index, α.
5) The Taguchi design with orthogonal array of L_9-3^4 (9 trials, 3 levels, 4 parameter settings) has been chosen for optimization of injection molding parameter.
6) The quality tests (warpage, shrinkage) and physical test (density, porosity) were conducted.
7) Fabrication of WC-6Co using compaction method start with the mixing process consist of WC-6Co powder and TiC powder (with different amount of wt. % (0.50, 0.75 and 1.0)).
8) The samples were compacted by using uniaxial hydraulic pressing machine with 3 tonnes of pressure by using the mould with diameter of 14mm.
9) The different holding time used were 15 minutes, 30 minutes and 45 minutes with a sintering temperature of 378ºC.
10) Characterization on the sintered metal included phase analysis by using Energy Diffraction X-Ray (EDX) and X-Ray Diffraction (XRD) and grain size analysis. Meanwhile the physical properties of WC-6Co were perform using density test and micro hardness test.

1.5 Significance of Study

The findings of this study on optimization of parameter setting for MIM will redound to the benefit of hard metal industry considering that MIM plays an important role in the manufacturing process today. Greater demand on WC-Co justifies the need for more effective approaches. Thus, application of the recommended approach derived from the result of this study will be able to develop a better product in the future. It will also be helpful to understand the materials used in the study such as WC-Co and TiC to be used in future studies. Besides, it will be helpful for researchers who are interested in doing advance work and uncover critical areas in such material which is rarely explored by many researchers on the same topic. This study can help us to get the idea of grain growth inhibitor as well as rheological properties which is important for the MIM industry. Similarly, we know that the Taguchi method is generally used for the optimization process, thus we can get the overview about the Taguchi method in order to obtain a good parameter setting. This study will contribute to the improvement of MIM process in engineering not only for study, but also for industrial purposes. Hopefully, this research will encourage others to be drawn into this scope of research and to make this beneficial for their future research. Thus, the outcomes of the present study is considered beneficial for students as well as researchers.

1.6 Summary

Chapter 1 explains the overall process of the study. In the background study, it is highlighted that the powder injection molding is a manufacturing process used to fabricate small and complex part for large quantity of product. Since nano powder contributes to several advantages, various studies with PIM were conducted using nano powder material. In the problem statement, three problems are identified which reflects the objectives of the study. The characterization of the feedstock is the most crucial step in order to obtain the physical and thermal properties of the raw material for a good feedstock to reduce the overall defect on the product. In conjunction to the production cost and product quality, the optimization process of the injection molding parameter is carried out. The compaction process is chosen to fabricate the sample and the characteristic of the sintered sample were analyzed.

This thesis consists of five chapters. The first chapter explains the introduction and background of the study including research problems, objectives, and scope of the study. The literature review related to the MIM process in particular to the WC-Co including the grain growth inhibitor used, binder system and also the explanation of the process is written in the second chapter. The third chapter explains the procedure of experimental and detailed study methodology with the instrument used throughout the research. The results of the experiment that starts from the characterization stage of the raw materials, preparation of the feedstock to the result of injection molding, and the sintered samples analysis are described in the fourth chapter. Finally, the fifth chapter includes the conclusions and contributions of research, and proposals for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter elaborates about the materials used for the study, metal injection molding (MIM) cycle, and its processes, as well as the characterization used for the test sample produced. Explanation of parameter that influenced the process of MIM, material chosen in this study, reasons for choosing MIM in this study, and its advantages are also discussed in this chapter. Besides, the meaning of part quality, which includes warpage, shrinkage, density, and a brief explanation of the theory of Taguchi orthogonal array are also focused in this chapter.

2.2 Cemented Carbide Injection Molding

Cemented Tungsten Carbide (WC-Co) has been widely used in the manufacturing industry, due to its excellent properties. Generally, WC-Co with high cobalt content has high and low hardness, and vice versa (Liu et al., 2014). Thus, the fracture toughness is improved. Enhanced mechanical properties of the ultrafine grained WC-Co was compared to the traditional coarse grained WC-Co materials. On shock environment, the fracture toughness of ultrafine hard metals can influence the application compared to that of coarse grained cemented carbides (Zhao, 2009). The ultrafine WC- (micron WC-Co) systems (Armstrong, n.d).

Basically, the microstructures and mechanical properties of WC-Co materials are affected by many factors during production. According to Liu et al. (2014), within the air classification method, different granularity levels of WC powders are obtained owing to the effect of the matching of coarse and fine powders on the mechanical properties and microstructures of WC-10Co cemented carbides. A study reported that the fracture toughness is influenced by WC particle size on WC-Co cemented carbides and the mechanism of particle size. However, there is no systematic investigation on the microstructure and fracture mechanism of the ultrafine WC (micron WC-Co) hard metals.

The cemented carbide was formed by using three individual phases. The classification of cemented carbides was just only for metal-cutting applications. However, according to Sandvik (2008), their developed cemented carbide falls into four main groups. The first group is called WC-Co grades which contains WC and Co only (i.e. two-phases) and a few trace elements. WC-grain sizes range between ultra-fine WC grain sizes (< 0.5µm) until 5µm. Good mechanical properties can be achieved with such fine, uniform grain size. The second group is called corrosion resistant grade which contains cemented carbide in which the binder has been specifically designed to improve corrosion resistance. Dual Property (DP) grade is a new concept which enables components to be produced containing individual microstructural zones with different binder content. Lastly, the grade with a cubic carbide is designed to provide a good balance of wear resistance and toughness in applications. Figure 2.1 shows the grain size classification for standard grade.

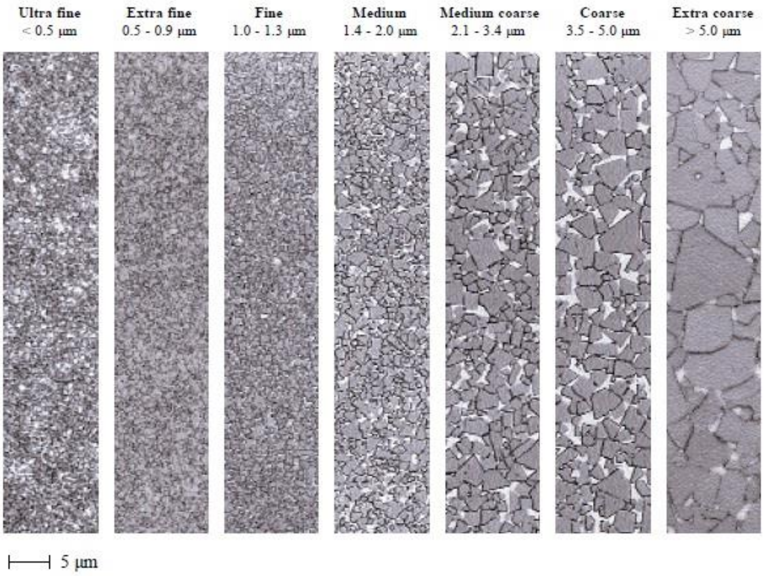

Figure 2.1: The grain size classification for standard grade (Sandvik, 2008)

Injection molding process of WC-Co involves several steps that combine both conventional Powder Metallugy (P/M) and Plastic Injection Molding and well known as metal injection molding (MIM). Small and complex shaped components are manufactured effectively for high performance applications using PIM process. Metal powder and binders are two main components needed in injection molding. The powder used in this study is tungsten carbide-cobalt cemented carbide as this material has good properties such as high hardness and wear resistance with sufficient ductility and toughness (Chuankrerkkul et al., 2008). Generally, the PIM process consists of several steps, including feedstock preparation by mixing the powder with a removable binder. The feedstock is shaped during injection molding process and the green part then rebounds to remove the binders, and finally sintered (Yang & German, 1998).

The PIM process is illustrated in Figure 2.2 shows the sequence of the process which begins with the selection of metal powder and binder. After mixing at a certain ratio using a mixing machine, the feedstock should be homogeneous and free from powder-binder separation (Supati et al., 2000). The feedstock is usually in the form of pellets similar to the granules. Then the feedstock must undergo the granular process to form the appropriate granule size to inject with the injection machine. The molding stage is quite a simple and straight forward process. It is done in the exact same way as regular injection molding of plastic parts: feedstock is loaded into the injection molding machine and the machine drives the screw filling the mold. Next under the control of several injection parameters, the feed material is injected at a certain pressure to form the anum body. Following the injection molding is debinding. The debinding stage is designed to get rid of the polymer binder material from the molded part, making it purely metal.

There are many binding methods used, and the selection depends on the type of binders found in one feed material. Among the commonly used methods are the solvents of the solution and also the thermal properties (Liu et al., 2008), and products that have undergone the binding process are known as war bodies. At the sintering stage the now pure metal powder part is heated up to near melting temperatures. The high temperature makes the particles of the metal powder fuse together, increasing the density and strength of the part. A well performed sintering provides the MIM-produced part with properties similar to that of a die casted. (German & Bose, 1997). Finally, in order to achieve high-density final products, the war body will be through the process of confinement where war bodies are subject to heat heating and shrinkage occur depending on the percentage of chargeable ports. The sintered body usually reaches almost equal density of theory that is 97% (German & Bose, 1997).

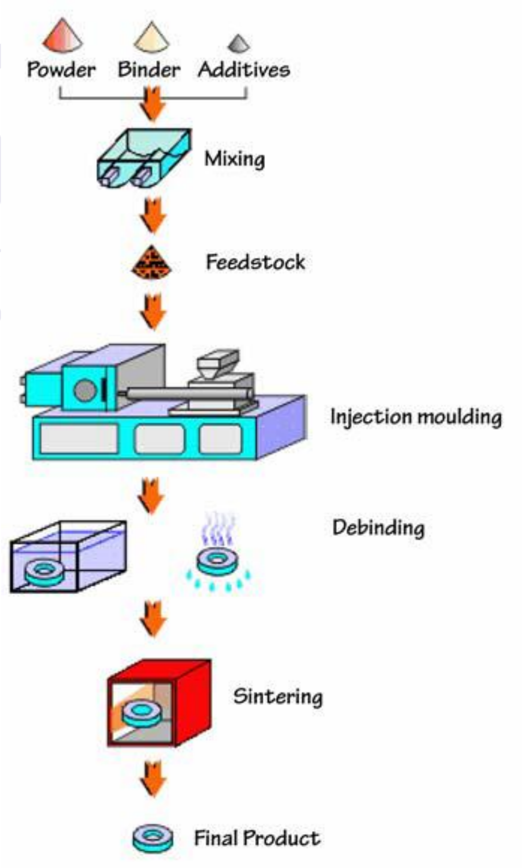

Figure 2.2: Metal injection molding (MIM) process (Chuankrerkkul et al., 2007)

REFERENCES

Aggarwal, G., Park, S. J., & Smid, I. (2006). Development of niobium powder injection molding: Part I. Feedstock and injection molding. *International Journal of Refractory Metals and Hard Materials*. 24(3): 253–262.

Abolhasani, H. and Muhamad, N. (2010). A new starch-based binder for metal injection molding. *Journal of Materials Processing Technology*. 210(6–7): 961–968.

Ahmad, S., Muhamad, N., Muchtar, A, Sahari, J., & Jamaludin, K. R. (2010). Development and Characterization of Titanium Alloy Foams. *International Journal of Mechanical and Materials Engineering*. 5(2): 244-250.

Al-Aqeeli, N. (2015). Characterization of nano-cemented carbides Co-doped with vanadium and chromium carbides. *Powder Technology*. 273: 47–53.

Amin, S. Y. M., Muhamad, N., Jamaludin, K. R., Fayyaz, A., & Yunn, H. S. (2012). Ball milling of WC-Co powder as injection molding feedstock. *Applied Mechanics and Materials*. 52(5): 1425–1430.

Amin, S. Y. M., Muhamad, N., & Jamaludin, K. R. (2013). Optimization of injection molding parameters for WC-Co feedstocks. *Jurnal Teknologi (Sciences and Engineering*. 63(1): 51–54.

Amin, S. Y. M., Muhamad, N., Jamaludin, K. R., Fayyaz, A., & Yunn, H. S. (2014). Characterization of the feedstock properties of metal injection-molded WC-Co with palm stearin binder system. *Sains Malaysiana*. 43(1): 123–128.

Aprajeeta, J., Gopirajah, R., & Anandharamakrishnan, C. (2015). Shrinkage and porosity effects on heat and mass transfer during potato drying. *Journal of Food Engineering*. 144: 119-12.

Armstrong RW, C. O. (n.d.). Indentation fracture mechanics toughness dependence on grain size and crack size: application to alumina and WC–Co. *International Journal of Refractory Metals and Hard Materials*. 24(1): 129-34.

Arifin, A., Sulong, A. B., Muhamad, N., Syarif, J., & Ramli, M. I. (2015). Powder injection molding of HA/Ti6Al4V composite using palm stearin as based binder for implant material. *Materials and Design*. 65: 1028–1034.

Asmawi, R., Ibrahim, M., & Amin, A. (2014). Mixing and Characterisation of Stainless Steel 316L Feedstock for Waste Polystyrene Binder System in Metal Injection Molding (MIM). *Applied Mechanics and Materials*. 607: 83–86.

Balbino, N. A. N., Correa, E. O., de Carvalho Valeriano, L., & Amâncio, D. A. (2017). Microstructure and mechanical properties of 90WC-8Ni-2Mo_2C cemented carbide developed by conventional powder metallurgy. *International Journal of Refractory Metals and Hard Materials*. 68: 49–53.

Bao, R. and Yi, J. (2013). Effect of sintering atmosphere on microwave prepared WC-8Co cemented carbide. *International Journal of Refractory Metals and Hard Materials*. 41: 315–321.

Bao, R. and Yi, J. (2014). Densification and alloying of microwave sintering WC–8wt. %Co composites. *International Journal of Refractory Metals and Hard Materials*. 43: 269–275.

Bierwagen, G. P. (1972). CPVC Calculations. *Journal of Paint Technology*. 44 (574): 46-55.

Chang, S. H. and Chang, P. Y. (2014). Study on the mechanical properties, microstructure and corrosion behaviors of nano-WC-Co-Ni-Fe hard materials through HIP and hot-press sintering processes. *Materials Science and Engineering: A*. 618: 56–62.

Chang, S. H. and Chen, S. L. (2014). Characterization and properties of sintered WC-Co and WC-Ni-Fe hard metal alloys. *Journal of Alloys and Compounds*. 585: 407–413.

Chen, H., Yang, Q., Yang, J., Yang, H., Chen, L., Ruan, J., & Huang, Q. (2017). Effects of VC/Cr_3C_2 on WC grain morphologies and mechanical properties of WC-6wt. %Co cemented carbides. *Journal of Alloys and Compounds*. 714: 245–250.

Chen, J., Liu, W., Deng, X., & Wu, S. (2016). Effects of Mo and VC on the microstructure and properties of nano-cemented carbides. *Science of Sintering*. 48(1): 41–50.

Chen, Y., Yang, Y., Yang, G., Wang, L., & Wu, M. (2018). Fabrication of WC-TiC-Co Cemented Carbide at Different Heating Rate by Micro-FAST process. *MATEC Web of Conferences*. 190: 10006.

Chuankrerkkul, N., Messer, P. F., & Davies, H. A. (2008). Application of polyethylene glycol and polymethyl methacrylate as a binder for powder injection moulding of hardmetals. *Chiang Mai Journal of Science*. 35(1): 188–195.

Contreras, J.M., Morales, A.J. & Torralba, J.M. (2010). Experimental and theoretical methods for optimal solid loading calculation in MIM feedstocks fabricated from powders with different particle characteristics. *Powder Metallurgy*. 53(1): 34-40.

Fabijanić, T. A., Jakovljević, S., Franz, M., & Jeren, I. (2016). Influence of Grain Growth Inhibitors and Powder Size on the Properties of Ultrafine and Nanostructured Cemented Carbides Sintered in Hydrogen. *Metals*. 6(9): 198.

Fayyaz, A., Muhamad, N., Sulong, A. B., Yunn, H. S., Amin, S. Y. M., & Rajabi, J. (2012). Effect of Dry and Wet Ball Milling Process on Critical Powder Loading and Mixture Properties of Fine WC-10Co-0.8VC Powder. *Jurnal Teknologi*. 59: 141–144.

Fayyaz, A., Muhamad, N., Sulong, A. B., Yunn, H. S., Amin, S. Y. M., & Rajabi, J. (2013). Rheological Properties of Cemented Tungsten Carbide Feedstock for Micro Powder Injection. *Materials Science Forum*. 773–774: 827–832.

Fayyaz, A., Muhamad, N., Sulong, A. B., Yunn, H. S., Amin, S. Y. M., & Rajabi, J. (2015). Micro-powder injection molding of cemented tungsten carbide: Feedstock preparation and properties. *Ceramics International*. 41(3): 3605–3612.

Gillia, O., Josserond, C., & Bouvard, D. (2001). Viscosity of WC-Co compacts during sintering. *Acta Materialia*. 49(8): 1413–1420.

German, R. M. and Bose Animesh. (1997). *Injection molding of metals and ceramics*. New Jersey: metal powder industries federation.

German, R. M. (2014). *Chapter Ten - Sintering With External Pressure*. *Sintering: from Empirical Observations to Scientific Principles*. Elsevier Inc.

German, R. M. (2014). *Consolidation Techniques*. *Comprehensive Hard Materials* (Vol. 1). Elsevier Ltd.

German, R. M. (2013). Progress in titanium metal powder injection molding. *Materials*. 6(8): 3641–3662.

German, R. M. (2013). Rapid Heating Concepts in Sintering. *Journal of Korean Powder Metallurgy Institute*. 20(2): 85–99.

German, R. M., Suri, P., & Park, S. J. (2009). Review: Liquid phase sintering. *Journal of Materials Science*. 44(1): 1–39.

Groover, P. M. (2010). *Fundamentals of Modern Manufacturing, materials, Processes, and Systems.* United States, America: John Wiley & Sons. Inc.

Guimarães, B., Figueiredo, D., Fernandes, C. M., Silva, F. S., Miranda, G., & Carvalho, O. (2019). Laser machining of WC-Co green compacts for cutting tools manufacturing. *International Journal of Refractory Metals and Hard Materials*. 81: 316–324.

Hamidi, M. F. F. A., Harun, W. S. W., Samykano, M., Ghani, S. A. C., Ghazalli, Z., Ahmad, F., & Sulong, A. B. (2017). A review of biocompatible metal injection moulding process parameters for biomedical applications. *Materials Science and Engineering: C*. 78: 1263–1276.

Heaney, D. F. (Ed.). (2012). Metal injection molding (MIM) of titanium and titanium alloys. *Handbook of Metal Injection Molding, Woodhead Publishing*. 415–445.

Heng, S. Y., Muhamad, N., Bakar, A., Fayyaz, A., & Amin, S. M. (2013). Effect of sintering temperature on the mechanical and physical properties of WC – 10 % Co through micro-powder injection molding (μPIM), *Ceramics International*. 39: 4457–4464.

Hezhou, Y., Xing, Y.L. & Hanping, H. 2008. Fabrication of metal matrix composite by metal injection molding- A review. *Journal of Materials Processing Technology*. 200: 12-24.

Huang, S. G., Liu, R. L., Li, L., Van der Biest, O., & Vleugels, J. (2008). NbC as grain growth inhibitor and carbide in WC-Co hardmetals. *International Journal of Refractory Metals and Hard Materials*. 26(5): 389–395.

Huang, B., Liang, S., & Qu, X. (2003). The rheology of metal injection molding. *Journal of Materials Processing Technology*. 137: 132–137.

Ibrahim, M. H. ., Manaff, M. H. A., Othman, M. H., Mustafa, N., Masrol, S. R., & Rafai, N. H. (2014). Optimisation of Processing Condition Using Taguchi Method on Warpage for HDPE-Clay Composite. *Applied Mechanics and Materials*. 600: 28–32.

Iriany. (2002). *Kajian sifat reologi bahan suapan yang mengandungi stearin sawit untuk proses pengacuanan suntikan logam*. Universiti Kebangsaan Malaysia: Ph.D. Thesis.

Islam, M. N., & Pramanik, A. (2016). Comparison of Design of Experiments via Traditional and Taguchi Method. *Journal of Advanced Manufacturing Systems*. 15(3): 151–160.

Ismail, F., Omar, M. A., Subuki, I., Abdullah, N., Ali, E. A. G. E. & Hassan, N. (2007). Characterization of the feedstock for Metal Injection Moulding using biopolymer binder. *Proceeding of Advanced Processes and System in Manufacturing*. 85-92.

Istikamah Subuki. (2010). *Injection moulding of 316L stainless steel powder using palm stearin based binder system*. Universiti Teknologi Mara: Ph.D. Thesis.

Iswandi, Sahari, J., Sulong, A. B., & Husaini, T. (2016). Critical Powder Loading and Rheological Properties of Polypropylene/Graphite Composite Feedstock for Bipolar Plate Application. *Malaysian Journal of Analytical Sciences*. 20(3): 687 – 696.

Jabir, S. M., Noorsyakirah, A., Afian, O. M., Nurazilah, M. Z., Aswad, M. A., Afiq, N. H. M., & Mazlan, M. (2016). Analysis of the Rheological Behavior of Copper Metal Injection Molding (MIM) Feedstock. *Procedia Chemistry*. 19: 148–152.

Jain, K., Kumar D., & Kumawat, S. (2013). Engineering Plastic Injection Molding with Taguchi Approach - A Review. *International Journal of Scientific Research*. 2277: 147–149

Jamaludin, K. R., Muhamad, N., Rahman, M. N. A., Amin, S. Y. M., Ahmad, S., & Ibrahim, M. H. I. (2016). Sintering Parameter Optimisation of the SS316L Metal Injection Molding (MIM) Compacts for Final Density Using Taguchi Method. *The 3rd South East Asian Technical University Consortium (SEATUC) Symposium*. 258–262.

Jamaludin, M. I., Kasim, N. A. A., Nor, N. H. M., & Ismail, M. H. (2015). Development of porous Ti-6Al-4V Mix with palm stearin binder by metal injection molding technique. *American Journal of Applied Sciences*. 12(10): 742-751.

James, W. B. (2015). *Powder Metallurgy Methods and Applications*. ASM Handbook, Volume 7, Powder Metallurgy. ASM International.

Kaiser, A. and Lutz, R. (2011). Uniaxial hydraulic pressing as shaping technology for advanced ceramic products of larger size. *International Ceramic Review*. 60(3): 230-234.

Kamdani, K., Azriszul, M. A., & Thoufeili, T. (2015). Evalution of Porosity in metal Injection, *ARPN Journal of Engineering and Applied Sciences*. 11(18): 11188–11191.

Karatas, C., Kocer, A., Unal, H. I. & Saritas. (2004). Rheological properties of feedstocks prepared with steatite powder and polyethylene-based thermoplastic binders. *Journal of Materials Processing Technology*. 152: 77- 83.

Ke, D., Pan, Y., Lu, X., Hong, B., & Zhang, H. (2015). Influence and effectivity of Sm2O3and Cr3C2grain growth inhibitors on sintering of WCoB-TiC based cermets. *Ceramics International*. 41(10): 15235–15240.

Khakbiz, M., Simchi, A., & Bagheri, R. (2005). Analysis of the rheological behavior and stability of 316L stainless steel–TiC powder injection molding feedstock. *Materials Science and Engineering: A*. 407: 105–113.

Kong, X., Barriere, T., & Gelin, J. C. (2012). Determination of critical and optimal powder loadings for 316L fine stainless steel feedstocks for micro-powder injection molding. *Journal of Materials Processing Technology*. 212(11): 2173–2182.

Lang, S., Yan, Q., Sun, N., Zhang, X., & Ge, C. (2017). Effects of TiC content on microstructure, mechanical properties, and thermal conductivity of W-TiC alloys fabricated by a wet-chemical method. *Fusion Engineering and Design*. 121: 366–372.

Li, J., Cheng, J., Chen, P., Chen, W., & Wei, C. (2018). Fabrication of WC-Co cemented carbides with gradient distribution of WC grain size and Co composition by lamination pressing and microwave sintering. *Ceramics International*. 44(10): 11225–11232.

Li, S., Huang, B., Li, D., Li, Y. Liang, S. & Zhou, H. (2003). Influence of sintering atmosphere on densification process of injection moulded gas atomised 316L stainless steel. *Powder Metallurgy*. 46(3): 241-245.

Li, X., Liu, Y., Wei, W., Du, M., Li, K., Zhou, J., & Fu, K. (2016). Influence of NbC and VC on microstructures and mechanical properties of WC-Co functionally graded cemented carbides. *Materials and Design*. 90: 562–567.

Lin, N., He, Y., Wu, C., Liu, S., Xiao, X., & Jiang, Y. (2014). Influence of TiC additions on the corrosion behaviour of WC – Co hard metals in alkaline solution. *International Journal of Refractory Metals and Hard Materials*. 46: 52–57.

Liu, C., Lin, N., He, Y., Wu, C., & Jiang, Y. (2014). The effects of micron WC contents on the microstructure and mechanical properties of ultrafine WC-(micron WC-Co) cemented carbides. *Journal of Alloys and Compounds*. 594: 76–81.

Liu, G., Chen, J., Liu, M., Wan, X. (2012). Shrinkage, porosity and density behavior during convective drying of bio-porous material. *Procedia Engineering*. 31: 634-640.

Liu, Z. Y., Loh, N. H., Tor, S. B., Khor, K. A., Murakoshi, Y., & Maeda, R. (2001). Binder system for micro powder injection molding. *Materials Letters*. 48(1): 31–38.

Mahmoodan, M., Aliakbarzadeh, H., & Gholamipour, R. (2011). Sintering of WC-10%Co nano powders containing TaC and VC grain growth inhibitors. *Transactions of Nonferrous Metals Society of China (English Edition)*. 21(5): 1080–1084.

Marinov. V. (2008). *Manufacturing Process for Metal Products. North Dakota*. Kendal Hunt Publishing Company.

Megat-Yusoff, P. S. M., Latif, M. R. A., and Ramli. M. S. (2011). Optimizing injection molding processing parameters for enhanced mechanical performance of oil palm empty fruit bunch high density polyethylene composites, *Journal of Applied Sciences*. 11(9):1618–1623.

Merwe, R. V. D., & Sacks, N. (2013). Effect of TaC and TiC on the friction and dry sliding wear of WC-6 wt. % Co cemented carbides against steel counterfaces. *International Journal of Refractory Metals and Hard Materials*. 41: 94–102.

Morton, C. W., Wills, D. J., & Stjernberg, K. (2005). The temperature ranges for maximum effectiveness of grain growth inhibitors in WC-Co alloys. *International Journal of Refractory Metals and Hard Materials*. 23: 287–293.

Kurgan, N. (2014). Effect of porosity and density on the mechanical and microstructural properties of sintered 316L stainless steel implant materials. *Materials and Design*. 55: 235-241

Ning, W. Y., Muhamad, N., Sulong, A. B., Fayyaz, A., & Raza, M. R. (2015). Effects of vanadium carbide on sintered WC-10%Co produced by micro-powder injection molding. *Sains Malaysiana*. 44(8): 1175–1181.

Nor, N. H. M., Muhamad, N., Ihsan, A. K. A. M., & Jamaludin, K. R. (2013). Sintering parameter optimization of Ti-6Al-4V metal injection molding for highest strength using palm stearin binder. *Procedia Engineering*. 68: 359–364.

Oh, J. W., Lee, W. S., & Park, S. J. (2017). Influence of nano powder on rheological behavior of bimodal feedstock in powder injection molding. *Powder Technology*. 311: 18–24.

Pavlina, E. J. and Van Tyne, C. J. 2008. Correlation of Yield Strength and Tensile Strength with Hardness for Steels. *Journal of Materials Engineering and Performance*. 17(16): 125.

Qu, X., Gao, J., Qin, M., & Lei, C. (2005). Application of a wax-based binder in PIM of WC-TiC-Co cemented carbides. *International Journal of Refractory Metals and Hard Materials*. 23: 273–277.

Raza, M. R., Ahmad, F., Muhamad, N., Sulong, A. B., Omar, M. A., Akhtar, M. N., & Aslam, M. (2016). Effects of solid loading and cooling rate on the mechanical properties and corrosion behavior of powder injection molded 316 L stainless steel. *Powder Technology*. 289: 135–142.

Rumman, R., Chuan, L. C., Quinton, J. S., & Ghomashchi, R. (2019). Understanding the potential of microwave sintering on WC-Co. *International Journal of Refractory Metals and Hard Materials*. 81: 7–14.

Ruzlan, M. S. Draman, M. K. Hashim, M. H. Megat Ismail, M. S. Saruddin, M. S. S. Abdullah, Z. (2009). *Study of Abrasive Wear Behaviour on Aluminium Reinforced with 5-20.wt% Psc and Psbp Particles Fabricated via Conventional Powder Metallurgy*. Politeknik Tuanku Syed Sirajuddin: Tesis Diploma.

Sandvik. (2008). Cemented Carbide, Sandvik new developments and applications.

Shi, X., Shao, G., Duan, X., Zhang, W., & Yuan, R. (2005). Sintering of WC-10Co nanocrystalline composite powder. *Xiyou Jinshu Cailiao Yu Gongcheng/Rare Metal Materials and Engineering*. 34: 118–119.

Sotomayor, M. E., Varez, A., & Levenfoeld, B. (2010). Influence of powder particle size distribution on rheological properties of 316L powder injection molding feedstock. *Powder Technology*. 200: 30–36.

Su, W., Sun, Y. X., Yang, H. L., Zhang, X. Q., & Ruan, J. M. (2015). Effects of TaC on microstructure and mechanical properties of coarse grained WC-9Co cemented carbides. *Transactions of Nonferrous Metals Society of China (English Edition)*. 25(4): 1194–1199.

Sunil, B. R., Sivaprahasam, D., & Subasri, R. (2010). Microwave sintering of nanocrystalline WC-12Co: challenges and perspectives. *International Journal of Refractory Metals and Hard Materials*. 28: 180–186.

Suri, P., Atre, S. V., German, R. M., & De Souza, J. P. (2003). Effect of mixing on the rheology and particle characteristics of tungsten-based powder injection molding feedstock. *Materials Science and Engineering: A*. 356(1-2): 337–344.

Supati, R., Loh, N. H., Khor, K. A., & Tor, S. B. (2000). Mixing and characterization of feedstock for powder injection molding. *Materials Letters*. 46(2-3): 109–114.

Thummier, F., & Thomma, W. (1967). The Sintering Process. *Metals Materials*. 1: 69-108.

Tian, H., Peng, Y., Du, Y., Qiu, L., & Zhang, C. (2017). Thermodynamic calculation designed compositions, microstructure and mechanical property of ultra-fine WC-10Co-Cr 3 C 2 -TaC cemented carbides. *International Journal of Refractory Metals and Hard Materials*. 69: 11–17.

Upadhyaya, G. S. (2002). *Powder Metallurgy Technology*. Kanpur, India: Cambridge International Sciences Publishing.

Wang, W., Song, J., Yan, B., & Yu, Y. (2016). Metal injection molding of tungsten and its alloys. *Metal Powder Report*. 71(6): 441–444.

Wang, X., Fang, Z. Z., & Sohn, H. Y. (2008). Grain growth during the early stage of sintering of nanosized WC-Co powder. *International Journal of Refractory Metals and Hard Materials*. 26(3): 232–241.

Wu, C. C., Chang, S. H., Tang, T. P., Peng, K. Y., & Chang, W. C. (2016). Study on the properties of WC-10Co alloys adding Cr_3C_2 powder via various vacuum sintering temperatures. *Journal of Alloys and Compounds*. 686: 810–815.

Xiao, D. Hong, H. E., Hui, Y., Luo, Hong, D., & Song, M. (2009). Effect of VC and NbC additions on microstructure and properties of ultrafine WC-10Co cemented carbides. *Transactions of Nonferrous Metals Society of China (English Edition)*. 19(6): 1520–1525.

Xie, X. C., Lin, C. G., Jia, C. C., & Cao, R. J. (2015). Effects of process parameters on quality of ultrafine WC/12Co injection molded compacts. *International Journal of Refractory Metals and Hard Materials*. 48: 305–311.

Yang, M. J., & German, R. M. (1998). Nanophase and superfine cemented carbides processed by powder injection molding. *International Journal of Refractory Metals and Hard Materials*. 16(2): 107–117.

Yang, Q., Yang, J., Wen, Y., Zhang, Q., Chen, L., & Chen, H. (2018). A novel route for the synthesis of ultrafine WC-15 wt %Co cemented carbides. *Journal of Alloys and Compounds*. 784: 577–582.

Yizong, T., Ariff, Z. M., & Khalil, A. M. (2017). Influence of Processing Parameters on Injection Molded Polystyrene Using Taguchi Method as Design of Experiment. *Procedia Engineering*. 184: 350–359.

Youseffi, M. & Menzies, A. (1997). Injection moulding of WC-6Co powder using two new binder systems based on montanester waxes and water soluble gelling polymers. *Powder Metallurgy*. 40(1): 62-65.

Yunn, H.S., Muhamad, N., Sulong, A.B., Fayyaz, A. & Li, H.P. (2011). Critical solid loading and rheological study of WC-10Co. *Applied Mechanics and Materials*. 59: 97-102.

Zhao, S., Song, X., Wei, C., Zhang, L., Liu, X., & Zhang, J. (2009). Effects of WC particle size on densification and properties of spark plasma sintered WC-Co cermet. *International Journal of Refractory Metals and Hard Materials*. 27(6): 1014–1018.

Zhao, Z., Liu, J., Tang, H., Ma, X., & Zhao, W. (2015). Effect of Mo addition on the microstructure and properties of WC-Ni-Fe hard alloys. *Journal of Alloys and Compounds*. 646: 155–160.

Zheng, Y., Gu, F., Ren, Y., Hall, P., & Miles, N. J. (2017). Improving Mechanical Properties of Recycled Polypropylene-based Composites Using Taguchi and ANOVA Techniques. *Procedia CIRP*. 61: 287–292.

Zhu, B., Qu, X., & Tao, Y. (2002). Powder injection molding of WC-8%Co tungsten cemented carbide. *International Journal of Refractory Metals and Hard Materials*. 20(5-6): 389–394.